UCRL-JC-133188
Preprint

Non-Neutral Plasma Science Issues for Heavy Ion Drivers

John J. Barnard

This paper was prepared for submittal to
Workshop on Cost Effective Steps to Fusion Power
Los Angeles, CA
January 25-27, 1999

January 22, 1999

Lawrence Livermore National Laboratory

DISCLAIMER

Non-neutral plasma science issues for Heavy Ion Drivers

John J. Barnard
Lawrence Livermore National Laboratory

Workshop on Cost Effective Steps to Fusion Power,
Los Angeles, California
January 25-27, 1999

Introduction. The fundamental requirement for a heavy ion fusion (HIF) driver is to deliver a number of ion beamlets (tens to hundreds) at the required pulse energy, (~ 2-6 MJ), pulse duration (~10 ns), and final spot radius (~ 2 mm) dictated by the implosion and hohlraum physics of the target. This is accomplished in the induction accelerator approach to HIF by accelerating low density beams in the low energy part of the accelerator (~10^9 cm^{-3}), gradually increasing the beam density as the energy of the beams increases and the focusing requirements are eased, and then rapidly compressing the beam to the final high density state in drift compression and final focus sections of the machine. Longitudinally, a beam would be compressed from typically 25 meters out of the injector to about a meter at the target. Radially, a beam would typically be born from a few cm radius source and ultimately reach a ~2 mm spot, so factors of 10 to 30 in both radial and longitudinal directions must typically be attained.

The main plasma science issues for Heavy Ion Drivers are almost all concerned with mechanisms which prevent focusability at the target. Focusability would be thwarted if either the velocity spread of the beam (longitudinal or transverse) or space charge forces are too large, as will be discussed below. Pointing errors also effectively broaden the spot size, since multiple beamlets must overlay to form a well defined spot.

Other plasma science issues are less fundamental, but are nevertheless important because of their practical impact on the design of the accelerator. The minimization of beam halo (the low- density outer population of beam particles beyond the nominal beam radius) is important in order to avoid accelerator activation or the heating of superconducting magnets above their critical point. Similarly, charge-changing collisions with the residual gas and charge-changing collisions between ions within the beam both lead to beam loss and so also contribute to unwanted activation and/or heating.

Six-dimensional phase space constraint. Simple geometric considerations show that, when passing through a final focusing optic, a transverse velocity spread Δv_x must be less than $v_z r_s/d$, where v_z is the longitudinal velocity, r_s is the spot size and d is the focal length of the final focusing optic, in order to have a focal spot radius less than r_s. Since d is limited by chamber considerations, Δv_x is strictly limited. In the longitudinal direction Δv_z is also constrained. In heavy ion fusion the final focus is usually envisioned to be accomplished using magnetic quadrupolar focusing. Chromatic aberration then limits the longitudinal spread Δv_z to less than approximately $v_z r_s/6\theta d$ where θ is the convergence half-angle onto the target. Thus, the velocity spread in all three directions, as well as the spatial extent in all three dimensions, is limited. However, Liouville's theorem requires that the phase space density ($dN/dxdydzdp_xdp_ydp_z$ where N is the number of particles, and p_x, p_y and p_z are the Cartesian momenta) must be preserved. Because non-linear forces can cause the phase space of the beam to engulf empty space, the macroscopic phase space volume can only (under most circumstances) get bigger. So it is useful to compare the initial phase space volume to that required at the target: $(r_s^2\, \Delta z\, \Delta p_x\, \Delta p_y\, \Delta p_z\, N_{beam})_{final}/(a^2\, \Delta z\, \Delta p_x\, \Delta p_y\, \Delta p_z\, N_{beam})_{initial} \sim 600$. Here Δp_x, Δp_y, and Δp_z, are the rms momentum spreads, a is the initial source radius of a single beam, and N_{beam}

represents the number of beams at either the source (subscript initial) or target (subscript final). We have assumed that the initial transverse velocity spreads Δv_x and Δv_y are of order $10^{-6}c$ (corresponding to a 0.1 eV source temperature) and that $\Delta v_z/v_z$ is of order 0.001 (arising from voltage injection errors). This factor of order 1000 of allowable increase in the effective 6D phase volume, implies a factor of 10 increase in normalized emittance (projected phase space area) in each of the Cartesian directions. The factor of ten has large error bars depending on what choices are made in the accelerator design; other design choices may provide more leeway.

Emittance Growth Phase space dilution (emittance growth) occurs when non-linear force profiles allow the phase space occupied by the beam to engulf empty space. Non-linearities arise from space charge, and from the focusing system (and from the accelerating system in the longitudinal case). In space-charge dominated beams the space-charge non-linearities occur largely at the edges of the beam, radially (in the Debye sheath) and longitudinally (in the beam ends). Further, the beam becomes susceptible to non-linear phase mixing when the beam becomes mismatched (i.e. undergoes oscillations of the normal envelope modes). Maintaining machine errors below well defined tolerances is thus essential to minimizing emittance growth. Simulations are crucial in determining the specific-tolerance for each category of machine errors.

Instabilities A number of potential instabilities have been investigated in HIF drivers. Temperature anisotropy instability arises when the longitudinal temperature is sufficiently smaller than the transverse temperature, and amplifies internal beam modes. S and leads to saturation occurs when the longitudinal temperature is around one third of the transverse temperature. Longitudinal resistive instability occurs when the resistance of the induction modules interacts with the beam, amplifying space charge waves that are backward propagating in the beam frame. Beam-break-up instablility occurs when high frequency waves in the cavities formed by the induction modules interact transversely with the beam. Two-stream instability can occur when the beam enters the chamber and interacts with the residual gas. All of the instabilities mentioned have analytically derived linear growth rates, and designs of the accelerator are constrained such that each growth rate is sufficiently small, (or saturation sufficiently benign) that the instabilities have minimal impact on emittance or centroid position.

Space Charge From an "envelope equation" we may describe the evolution of the beam size and estimate the allowable space charge that may be focused onto a target. To reduce the effect of space charge the accelerator designer must either distribute the charge over a larger number of beams, or provide neutralizing electrons within the target chamber, or accelerate to a high enough kinetic energy that space-charge effects become negligible (as the required currents [for a fixed pulse energy, or more precisely fixed target yield] and perveance [current/energy$^{3/2}$] are reduced). The neutralizing electrons may arise from pre-ionization of the entire chamber (or of a channel through which each beam passes), from coinjected electrons, or from foils placed at the chamber entrance which may be rapidly replaced if they suffer beam-induced damage. Increasing the energy and number of beams requires no new understanding of physics, but it may impact cost. Beam neutralization introduces new physics, but is amenable to simulations.

Experimental Status A sequence of small, scaled experiments over the last two decades has answered many of the most fundamental issues regarding transport of space-charge dominated beams. (In a space-charge dominated beam the space charge energy density is much greater than the thermal energy density within the beam). The Single Beam Transport Experiment (SBTE) verified that stable beam propagation, with little emittance growth, can occur over the length of the accelerator (in this case approximately 90 lattice elements), for highly space-charge dominated beams, allowing economic transport of high current beams. The Multi-Beam Experiment (MBE-4) demonstrated multiple beam transport, acceleration, and longitudinal compression using head-to-tail velocity tilts, all necessary elements of a HIF driver. The impact of space-charge, image, and external focusing non-linearities on emittance growth over 70 lattice elements was also assessed in MBE-4. At the University of Maryland, a number of experiments using low energy electron beams have shed light on space-charge dominated beam physics, including emittance growth during beam merging, space-charge waves, and longitudinal instability. Emittance growth of space-charge dominated beams in bends is being addressed by experiments in the Small Recirculator experiments at LLNL, which currently constitute one quarter of a ring, and also will be addressed at the University of Maryland electron ring, now being constructed. When completed, multi-lap operation in both rings would assess beam stability for ~1000's of lattice elements, comparable to the number of quadrupoles in a linac driver. The beam combiner experiment has demonstrated emittance growth close to the theoretical predictions when four beams are merged into one. The scaled final focus experiment has also demonstrated the ability to reach predicted values of final spot sizes. As the program emphasis shifts to driver-scale experiments, the Electrostatic Quadrupole (ESQ) injector offers a low emittance, 0.8 ampere potassium ion beam, providing a line charge density comparable to a driver and permitting detailed comparison of simulation with experiment.

Conclusion The main non-neutral plasma science issue in heavy ion drivers is focusability at the target. Considerations of the intrinsic six-dimensional phase volume at the beginning of the accelerator, and the required six dimensional phase volume required at the target, suggests there exists accelerator designs in which there is a reasonably large leeway to allow adequate focusability. Space-charge effects may also be controlled by properly designed neutralization methods, or large beam numbers, or high beam kinetic energy (and hence reduced currents for fixed target yield). Known beam instabilities also must be considered in the accelerator design. Errors in the focusing and accelerating systems also contribute to emittance growth. Simulations must play a crucial role in determining the level of errors that allow the accelerator to meet the focusing requirements, and in ensuring that beam instabilities are benign.